The fate of Earth's ocean

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Abstract

Questions of how water arrived on the Earth's surface, how much water is contained in the Earth system as a whole, and how much water will be available in the future in the surface reservoirs are of central importance to our understanding of the Earth. To answer the question about the fate of the Earth's ocean, one has to study the global water cycle under conditions of internal and external forcing processes. Modern estimates suggest that the transport of water to the surface is five times smaller than water movement to the mantle, so that the Earth will lose all its sea-water in one billion years from now. This straightforward extrapolation of subduction-zone fluxes into the future seems doubtful. Using a geophysical modelling approach it was found that only 27% of the modern ocean will be subducted in one billion years. Internal feedbacks will not be the cause of the ocean drying out. Instead, the drying up of surface reservoirs in the future will be due to the increase in temperature caused by a maturing Sun connected to hydrogen escape to outer space.

Keywords: Surface water reservoir, water fluxes, regassing, degassing, global water cycle

Introduction

Volatiles are of specific geochemical importance because they exert an important influence on a wide range of geological processes, e.g. the evolution and differentiation of the mantle and crust, the geophysical and rheological properties of materials that form the Earth, the formation of the atmosphere and the oceans, the appearance and evolution of life made possible by the changing environment of the early Earth and the nature of sedimentary processes and geochemical cycles. Among the volatiles water plays an important role. It is the necessary condition for the emergence and maintenance of life. Investigations of subduction-zone and spreading processes provide the key to the global water cycle. Efforts have been made to model this cycle to understand the past and future evolution of the various reservoirs of water within the Earth. There are different approaches to this problem. One approach examines the evolution of the different reservoirs by means of chemical geodynamics, i.e. the interactions between different-sized reservoirs of water are described by boxmodels. For this purpose, the abundance of water in the major reservoirs must be quantified, and the exchange fluxes between the reservoirs and the type of feedback mechanisms influencing the system have to be identified. Another approach applied here is based on a thermal evolution model with water-dependent rheology, i.e. water exchange between the reservoirs is directly coupled with the thermal history of the Earth. Here, the temporal variation of the water reservoirs is a direct result of the modelling and no knowledge of the exchange fluxes is necessary. This method requires the assessment of how much water is present in the Earth system. According to the pyrolite mantle model of Ringwood (1975) an amount of water of between 4 to 21 times the mass of the present ocean ($1.4 \cdot 10^{21}$ kg) could be contained in the entire system. Applying a crystallographic model for hydrous wadsleyite which may contain up to 3.3% H_2O by weight, Smyth (1994) predicted that the Earth mantle reservoir could contain more than four times the amount of water currently in the hydrosphere, which is equivalent to five times the mass of the entire modern ocean. Other estimates for mantle water abundance are as follows: the mantle nodules (Wänke *et al.*, 1984) suggest from 1.9 to 3.7 times the mass of the present-day ocean, the magma ocean model (Liu, 1988) 10 times, the Earth accretion model (Ahrens 1989) more than twice, and the measurements of K_2O/H_2O ratio (Jambon and Zimmerman, 1990) between 1.6 and 5.4 times the current ocean mass. For a summary see Table 1.

Bose and Navrotsky (1998) stated that there is no barrier to subducting substantial amounts of water to depths of 400–

Table 1. Different estimations of mantle water abundance

Reference	*Mantle water abundance (ocean masses)*
Ringwood (1975)	3–20
Smyth (1994)	4
Wänke et al. (1984)	1.9–3.7
Liu (1988)	10
Ahrens (1989)	> 2
Jambon and Zimmermann (1990)	1.6–5.4

600 km in colder slabs, since the slab can remain in the stability field of hydrous phases throughout its descent. Evidence for the presence of water in the upper mantle is provided by seismic tomography (Nolet and Zielhuis, 1994), excess helium in groundwater (Torgersen *et al*., 1995) and deep-focus earthquakes (Meade and Jeanloz, 1991).

In order to get input data for boxmodels or to prove results of evolution models one needs to ascertain modern subduction-zone water fluxes. These reservoir exchange fluxes can be determined with the help of sophisticated geochemical investigations. Rea and Ruff (1996) determined the subducting flux to be $9 \cdot 10^{11}$ kg yr^{-1} by means of combining lithologic data with convergence rates at convergent plate boundaries. Bebout (1996) calculated values for the subducting flux of between 9 and $19 \cdot 10^{11}$ kg yr^{-1} with the help of isotopic and trace element data and volatile contents for the Catalina Schist, the Franciscan Complex and eclogite-facies complexes in the Alps. Javoy (1998) linked the process of the Earth's accretion to stable isotope characteristics and presented a value for the subducting flux of $10 \cdot 10^{11}$ kg yr^{-1}. A recent result is based on phase diagrams of MORB+water and peridotite+water under mantle conditions, together with Benioff plane temperature estimates from seismological and petrological observations of active subduction-zones. Maruyama (1999) determined the water transport to the surface by magma to be $2.33 \cdot 10^{11}$ kg yr^{-1} and the water transport into the mantle from the surface to be $11.2 \cdot 10^{11}$ kg yr^{-1}.

Water is drawn from the surface reservoirs by the subduction of the ocean floor (subducting flux). Not all the subducted water is transported into the deep mantle (regassing flux). A fraction of it returns to the surface via back-arc or andesitic volcanism (recycling flux). Outgassing of water from the mantle occurs at the mid-ocean ridges (outgassing flux). The geophysical description of these processes and the implementation of them into a general thermal evolution model for the Earth open the possibility of modelling the water cycle on a theoretical foundation. It will be shown that the application of a simple parameterised convection model with water-dependent rheology provides the means to determine the quantity of modern subduction-zone water fluxes and their temporal variation from the Hadean to the far future.

Method

Parameterised convection models of whole mantle convection (Sleep, 1979; Schubert, 1979; Schubert *et al*., 1980; Christensen, 1985) have been used to investigate the thermal history of the Earth and to infer some physical mantle properties. The introduction of volatile-dependent rheology into these models allows the degassing and regassing history of the Earth to be elucidated. First steps to assess the influence of volatiles on mantle viscosity were made by Jackson and Pollack (1987). A first self-consistent model was proposed by McGovern and Schubert, (1989) and developed further by Franck and Bounama (1995a, b).

Under the condition of energy conservation, the time rate of change of the average mantle temperature T_m can be written as

$$\frac{4}{3}\pi\rho c(R_m^3 - R_c^3)\dot{T}_m = -4\pi R_m^2 q_m + \frac{4}{3}\pi Q(R_m^3 - R_c^3) \quad (1)$$

where ρ is the density, c is the specific heat at constant pressure, q_m is the heat flow from the mantle, Q is the energy production rate by decay of radiogenic heat sources in the mantle, and R_m and R_c are the outer and inner radii of the mantle, respectively. Core heat flow is not included because it has no major influence on the mantle devolatilisation. The mantle heat flow is a function of the mantle viscosity. As the Earth's body cools, the average mantle temperature and the mantle heat flow decrease over time, while mantle viscosity increases. The thermostatic effect of temperature- and strongly water-dependent mantle viscosity regulates the rate of mantle cooling (Fig. 1). Throughout most of the Earth's history, cooling is gradual, at about 100 K Gyr^{-1}. Examples of the evolution of T_m are shown in Franck *et al.* (1999).

Water from the mantle degasses at the mid-ocean ridges. The outgassing flux F_{out} depends on the density of water in the mantle ρ_w, the melt generation depth d_m, i.e., the depth where ascending mantle material intersects the basalt eutectic and extensive melting and melt segregation occurs, the outgassing fraction of water f_w and the areal spreading rate SR:

$$F_{out} = \rho_w d_m f_w SR \quad (2)$$

The density of water in the mantle can be expressed as

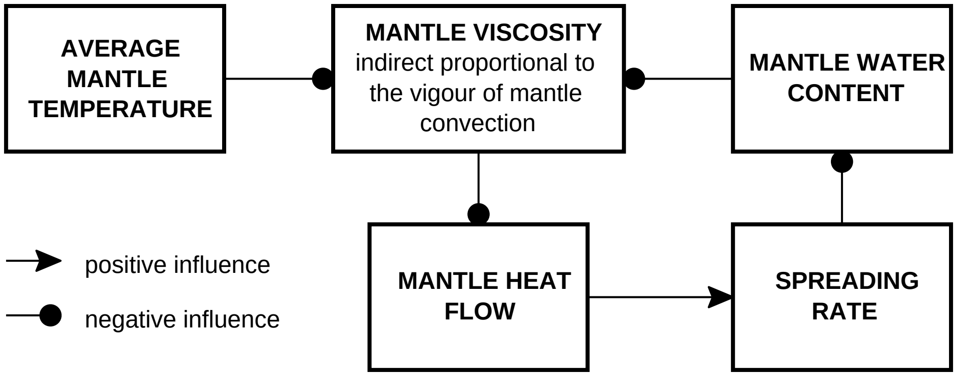

Fig. 1. *General scheme of the water exchange between mantle and surface reservoirs.*

$$\rho_w = (M_{\mathrm{tot}} - M_{\mathrm{surf}}) / V_m \qquad (3)$$

where M_{tot} is the total amount of water in the Earth system, M_{surf} is the mass of water in the surface reservoirs and V_m is the volume of the mantle. The areal spreading rate is a function of q_m, T_m and the area of the ocean basins A_0:

$$\mathrm{SR} = \frac{q^2_m \pi \kappa A_0}{4k^2 (\mathrm{T}_m - T_s)^2} \qquad (4)$$

where κ is the thermal diffusivity, k is the thermal conductivity and T_s is the surface temperature. A_0 is derived from the continental growth model of Condie (1990) as the difference of the area of the Earth and the continental area. The melt generation depth is a function of T_m and parameterised according to McKenzie and Bickle (1988). The constants used in all calculations are summarised in Table 2.

The regassing flux F_{reg} is directly proportional to the water content in the basalt layer f_{bas}, the average density ρ_{bas} and the thickness d_{bas} of the basalt layer before subduction, the areal spreading rate, and the regassing ratio of water R_{H2O}, i.e. the fraction of subducting water that actually enters the deep mantle:

$$F_{\mathrm{reg}} = f_{\mathrm{bas}}\, \rho_{\mathrm{bas}}\, d_{\mathrm{bas}}\; SR\; R_{H2O} \qquad (5)$$

The regassing ratio is the quotient of the regassing flux F_{reg} and the subducting flux F_{sub}. The resulting recycling flux

Table 2. Constants used in the thermal evolution model

Constant	*Value*	*Remarks*
d_{bas}	5×10^3 m	Average thickness of the basalt layer
f_{bas}	0.03	Mass fraction of water in the basalt layer
f_w	0.194	Degassing fraction of water
k	4.2 J s^{-1} m^{-1} K^{-1}	Thermal conductivity
$M_{\mathrm{surf}}(0)$	1.4×10^{21} kg	Initial amount of surface water, one ocean mass
M_{tot}	6.58×10^{21} kg	Total amount of water in the Earth system
R_c	3471×10^3 m	Inner radius of the mantle
R_m	6271×10^3 m	Outer radius of the mantle
$T_m(0)$	3000 K	Initial mantle temperature
T_s	273 K	Surface temperature
V_m	8.6×10^{20} m^3	Volume of the mantle
κ	10^{-6} m^2 s^{-1}	Thermal diffusivity
ρ_{bas}	2950 kg m^{-3}	Density of the basalt
ρc	4.2×10^6 J m^{-3} K^{-1}	Density and specific head

F_{cyc} is:

$$F_{cyc} = F_{sub} - F_{reg} \tag{6}$$

The differential equation for the mass of water in the surface reservoirs M_{surf} based exclusively on internal processes is simple:

$$\dot{M}_{surf} = F_{out} - F_{reg} \tag{7}$$

A general scheme of water exchange between mantle and surface reservoirs is depicted in Fig. 2.

The initial conditions have a strong influence on the model results. While the distribution of water in the surface and mantle reservoirs at the beginning of evolution is of minor importance, the amount of water considered in the Earth system as a whole has a significant effect, as does the introduction of time dependent R_{H2O}. For the total amount of water in the system, we take a mean value, in agreement with Jambon and Zimmermann (1990), of 4.7 times the current ocean mass and assume a distribution whereby the initial/recent surface reservoir contains one present-day ocean mass and the mantle reservoir 3.7 times the ocean mass. The variation of the regassing ratio with time is given by a simple linear dependence on the change of mean mantle temperature T_m which is derived from the thermal evolution model:

$$R_{H2O}(t) = m \cdot (T_m[0] - T_m[t]) + R_{H2O}(0) \tag{8}$$

The factor m is adjusted to get the correct modern amount of surface water (one ocean mass) and $R_{H2O}(0)$ is fixed at 0.001, i.e. the value is very low at the beginning of the Earth's evolution because of the enhanced loss of volatiles resulting from back-arc volcanism at higher temperatures. The influence of external processes on the thermal evolution is not considered because the model is formulated under the condition of mass and energy conservation within the Earth system.

There is a number of investigations on influx rates to Earth of volatiles from extraterrestrial sources derived from comets or other primitive solar system material. The generally accepted estimate for such volatile accretion rates is 10^7–10^8 kg yr^{-1} (Tuncel and Zoller, 1987). The resulting contribution to the total water reservoir in the Earth system would be of minor importance. In contradiction there is also a so-called extraterrestrial volatile-accretion hypothesis (ETV) postulating four to five orders of magnitude higher volatile accretion rates (Deming, 1999). If so, this effect would have to be taken into account as a water flux into the Earth system. In a first approximation Tuncel and Zoller (1987) is followed and the ETV is neglected.

Results and discussion

The model is run for a total of seven billion years, with 4.7 times the modern ocean mass of water in the entire system (of which one mass initially forms the surface reservoir) and the time-dependent regassing ratio according to Eqn.

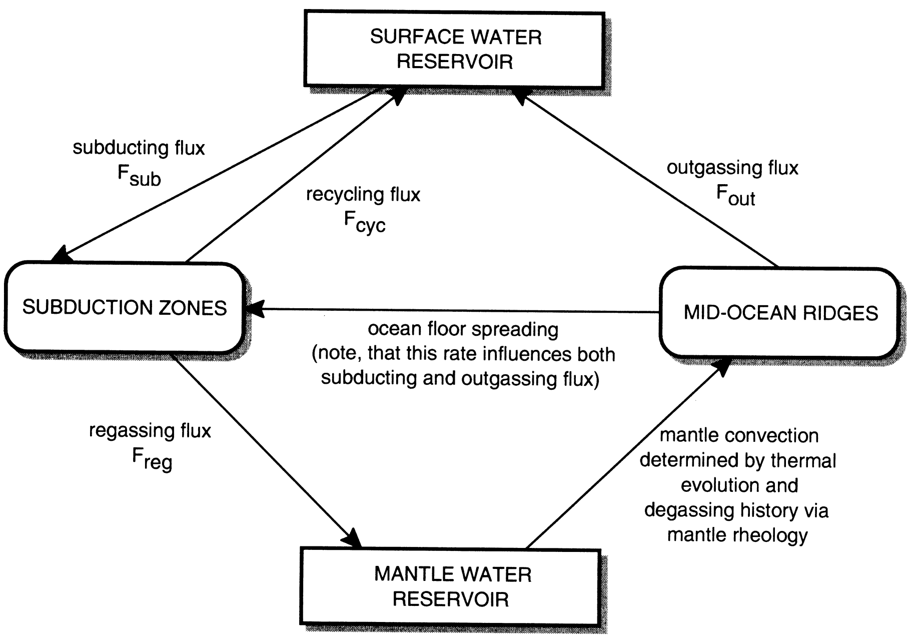

Fig. 2. *General scheme of the water exchange between mantle and surface reservoirs*

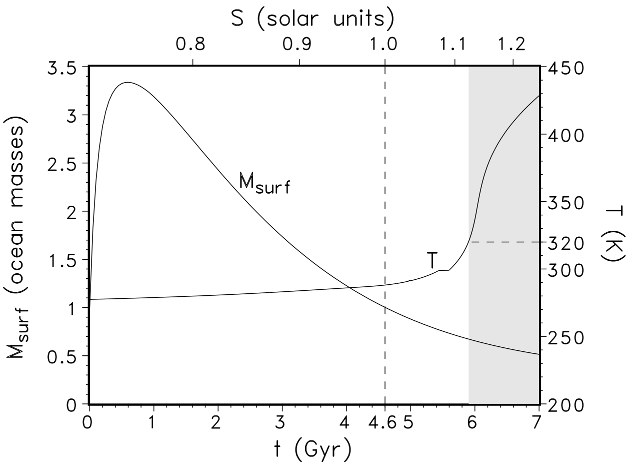

Fig. 3. *The evolution of the surface reservoir* M_{surf} *derived from the thermal evolution model, and of the mean global temperature* T *derived from the climate model of Caldeira and Kasting (1992). The region of temperatures higher than the critical value for the moist greenhouse model of Kasting (1988) is shaded grey. The values for the solar luminosity* S *are given in the upper scale.*

(8). The factor m was found to be $1.142 \cdot 10^{-3}$. R_{H2O} (4.6 Gyr), i.e. the recent regassing ratio, has a value of 0.661. This value is smaller than the geochemical investigations suggest. Bebout (1996) determined R_{H2O} in the range of 0.85 to 0.95 and Ito *et al*. (1983) put forward a value of 0.9. It is still uncertain how much of the subducted water is lost initially in forearcs due to devolatilisation, and the geochemically derived data are thus overvalued. The model result for R_{H2O} is therefore quite reasonable. The recent discovery of cold subduction zones (Liou *et al*., 2000), the sites of major recycling of water into the mantle, provides a new insight into subduction-zone processes and might lead to a re-evaluation of the geochemically derived fluxes.

Modern subduction-zone water fluxes have the following values: $F_{out} = 0.21 \cdot 10^{15}$ g yr^{-1}, $F_{sub} = 1.03 \cdot 10^{15}$ g yr^{-1}, $F_{reg} = 0.68 \cdot 10^{15}$ g yr^{-1}, and $F_{cyc} = 0.35 \cdot 10^{15}$ g yr^{-1}. The values for both the subducting flux and the outgassing flux correspond with the results of geochemical investigations. A comparison of fluxes and R_{H2O} with other results is given in Table 3.

The result for the temporal variation of the surface reservoir is shown in Fig. 3. It can be seen clearly that the surface reservoir never falls to zero and even shows a stabilising effect in the far future. In one billion years from the present, approximately 27% of the water in present-day surface reservoirs is subducted to the mantle. The adjustment of a quasi-equilibrium in the distant future would result in a maximum of 65% of surface water being subducted. These predictions regarding the magnitude of the future surface reservoir contradict the results of Maruyama (1999). Using values for the modern water fluxes which are comparable with our data, he derives a zero value for the surface reservoir in one billion years from the present. Our model results suggest that the temporal variations of the fluxes cannot be ignored. A reduction of the subducting flux since the Hadean of about two orders of magnitude is reasonable. It is not possible for the Earth to lose all the water in its surface reservoirs because of the feedback mechanisms between the internal sinks and sources.

The occurrence of liquid water on the Earth's surface is inextricably coupled with the global mean temperature. This temperature depends on solar luminosity. As a main sequence star, our Sun is getting brighter and hotter with time. With a 1-bar background atmosphere, the biggest change in stratospheric water vapour occurs at surface temperatures of between 320 K and 360 K. These results are obtained by a moist greenhouse climate model by Kasting (1988). As temperature increases, large amounts of evaporated ocean water are rapidly photo-dissociated, and this is followed by an escape of hydrogen into space. The runaway greenhouse effect would start at much higher

Table 3. Comparison of values for modern subduction-zone water fluxes and the regassing ratio between this and other studies

Reference	F_{out} (10^{15} g yr^{-1})	F_{sub} (10^{15} g yr^{-1})	F_{reg} (10^{15} g yr^{-1})	F_{cyc} (10^{15} g yr^{-1})	R_{H2O} (–)
This work	0.21	1.03	0.51	0.52	0.661
Ito *et al*. (1983)					0.9
Rea and Ruff (1996)		0.9			
Bebout (1996)		0.9 – 1.9		0.85 – 0.95	
Javoy (1999)		1	0.1		
Maruyama (1999)	0.233	1.12			

temperatures. To illustrate the onset of such a process, the evolution of the global temperature with increasing solar luminosity derived from the climate model of Caldeira and Kasting (1992) is plotted additionally in Fig. 3. After approximately 1.3 Gyr, a temperature of 320 K is reached and the Earth starts losing its water as a result of external forcing. This situation is far from present. The current rate of hydrogen escape from Earth's atmosphere is estimated to be $2.7 \cdot 10^8$ H atoms cm^{-2} s^{-1} (Hunten *et al.*, 1989). If this rate had remained constant for the last 4.5 Gyr, the quantity of water lost would correspond to 0.2% of the modern ocean mass.

Conclusions

Because of internal processes, the Earth cannot lose all the water in its surface reservoirs due to subduction processes to the mantle. After one billion years, only 27% of the modern ocean will be subducted into the mantle. If external forcing is left aside, in the far future a stabilisation of the surface reservoirs at a level of 65% of one present-day ocean mass could be expected. The fate of the Earth's ocean is sealed by external forcing. All water will disappear as a result of increasing global temperature caused by increasing solar luminosity. How long it will take before the Earth dries up completely still remains uncertain. First assessments suggest that a catastrophic loss of water will begin in 1.3 Gyr from the present or even sooner. Liquid water is essential for life. The question of the fate of the Earth's ocean is therefore inseparably connected to the question of the lifespan of the biosphere. Our results show that liquid water will be always available in surface reservoirs as a result of internal processes. The extinction of the biosphere will be caused by other limiting factors caused by the external forcing resulting from increasing solar luminosity (Lovelock and Whitfield, 1982; Caldeira and Kasting, 1992; Franck *et al.*, 2000).

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